“Flavored” Electric Dipole Moments in Supersymmetric Theories

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The Standard Model (SM) predictions for the hadronic electric dipole moments (EDMs) are well far from the present experimental resolutions, thus, the EDMs represent very clean probes of New Physics (NP) effects. Especially, within an MSSM framework with flavor-changing (but not necessarily CP violating) soft terms, large and potentially visible effects to the EDMs are typically expected. In this Letter we point out that, beyond-leading-order (BLO) effects, so far neglected in the literature, dominate over the leading-order (LO) effects in large regions of the parameter space, hence, their inclusion in the evaluation of the hadronic EDMs is unavoidable.

The Standard Model (SM) of elementary particles has been very successfully tested at the loop level both in (flavor-conserving) electroweak (EW) physics at the LEP and also in low-energy flavor physics. In particular, the two B factories have allowed an accurate determination of all the relevant parameters describing quark-flavor mixing within the SM. In this way, the overall picture of particle physics is a bit frustrating as far as the search for physics beyond the SM is concerned since little room is left for NP effects.

On the other hand, it is a common belief that the SM has to be regarded as an effective field theory, valid up to some still undetermined cut-off scale Λ above the EW scale. Theoretical arguments based on a natural solution of the hierarchy problem suggest that Λ should not exceed a few TeV, an energy scale that will be explored at the upcoming LHC.

Besides the direct search for NP at the scale (the so-called *high-energy frontier*), a complementary and equally important tool to shed light on NP is provided by high-precision low-energy experiments (the so-called *high-intensity frontier*). The latter are suitable in determining the symmetry properties of the underlying NP theory. Unfortunately, the hadronic uncertainties and the overall good agreement of flavor-changing neutral current (FCNC) data with the SM predictions prevent any conclusive evidence of NP effects in the quark sector. In this respect, the FCNC phenomenology in the lepton sector is definitively more promising. In fact, the extreme suppression predicted by the SM (with massive neutrinos) for processes like $\ell_i \to \ell_j\gamma$ implies that any experimental evidence for $\ell_i \to \ell_j\gamma$ would unambiguously point towards a NP signal.

The hadronic EDMs also offer a unique possibility to shed light in NP, given their strong suppression within the SM and their high sensitivities to NP effects. The minimal supersymmetric SM (MSSM), that is probably the most motivated model beyond the SM, exhibits plenty of CP-violating phases [1] able to generate the hadronic EDMs at an experimentally visible level [2]. These new CP phases may be introduced both in the flavor-conserving and in the flavor-changing soft SUSY breaking terms. In the latter case, the “flavored” EDMs are strongly constrained and/or correlated with FCNC processes from K and B physics.

In this Letter, we analyze the predictions for the “flavored” quark EDMs and Chromo-EDMs (CEDM), which contribute to the hadronic EDMs, at the BLO.

At the LO, the hadronic EDMs are generated by the one-loop exchange of gluinos ($\tilde{g}$) and charginos ($\tilde{\chi}^{\pm}$) with squarks. The dominant BLO contributions are computed by including all the one-loop induced ($\tan\beta$-enhanced) non-holomorphic corrections for the charged Higgs ($H^{\pm}$) couplings with fermions and for the $\tilde{\chi}^{\pm}/\tilde{g}$ couplings with fermions-sfermions. The above effective couplings lead to the generation of $H^{\pm}$ effects to the (C)EDMs, absent at the LO, via the one-loop $H^{\pm}$/top-quark exchange. Moreover, the chargino contributions, suppressed at the LO by the light quark masses, are strongly enhanced at the BLO by the heaviest-quark Yukawa couplings. Finally, also the gluino effects receive large BLO contributions that are comparable, in many cases, to the LO ones. As a result, BLO effects, so far neglected in the literature, dominate over the LO effects in large regions of the SUSY parameters space. Hence, their inclusion in the evaluation of the flavored (C)EDMs is mandatory.

The SM sources of CP violation are the QCD theta term $\overline{\theta}$ and the unique physical phase contained in the CKM matrix, V. However, a Peccei-Quinn symmetry [3] is commonly assumed making $\overline{\theta}$ dynamically suppressed. In this way, the hadronic EDMs can be generated by the only CP-violating phase of the CKM. The best way to describe them is provided by the Jarlskog invariants (JIs) that are a basis-independent measure of CP violation [4]. In the SM, the i-th quark EDMs d_{q_i} and CEDMs $d^c_{q_i}$ are induced by the flavor-conserving JIs,

$$J_{\rm SM}^{(d_i,u_i)} = {\rm Im}\left\{Y_d[Y_d,Y_u]Y_u y_{d,u}\right\}_{ii} \;, \tag{1}$$

where $y_d(y_u)$ is the down(up)-type quark Yukawa coupling constant and $Y_{d(u)} \equiv y_{d(u)}y^{\dagger}_{d(u)}$. Since $J_{\rm SM}^{(d_i,u_i)}$ are of the ninth order in the Yukawa coupling constants, the quark (C)EDMs are highly suppressed at the level of $\sim 10^{-(33-34)}\, e\,{\rm cm}$.

So, we conclude that the SM expectations for the

hadronic EDMs are well below the actual and expected future experimental resolutions [2].

Within a SUSY framework, CP-violating sources may naturally appear after the SUSY breaking through (i) flavor-conserving F-terms (such as the B parameter in the Higgs potential or the A terms for trilinear scalar couplings) and (ii) flavor-violating D-terms (such as the squark and slepton mass terms). In the case (i), the experimental bounds on the EDMs constrain the phases $\phi_{A,B}$ to be very close to zero: this naturalness problem is known as the SUSY CP problem [1]. In this respect, a mechanism leading to a natural suppression of the (C)EDMs would be desirable and, indeed, this is what happens in the case (ii).

The presence of flavor structures in the soft sector, that we parameterize as usual by means of the mass insertion (MI) parameters [5] $(\delta^q_{AA})_{ij} \equiv (m^2_{\tilde{q}_{AA}})_{ij}/m^2_{\tilde{q}}$ ($A = L/R$), generally leads to FCNC transitions and to (flavor-conserving/violating) CP-violating phenomena. As a natural consequence, the hadronic EDMs are generated and they turn out to be intimately linked to FCNC processes, as they both arise from the same source.

The size and the pattern of the MIs are unknown, unless we assume specific models. They are regulated by the SUSY breaking mechanism and by the interactions of the high-energy theories beyond the MSSM. In this way, it makes sense to study the individual impact of different kinds of MIs on the low-energy observables. When only $(\delta^q_{LL})_{ij} \neq 0$, the following flavor-conserving JI, which contributes to the down-quark (C)EDMs, shows up,

$$J^{(d_i)}_{LL} = \mathrm{Im}\left\{[Y_u, \delta^q_{LL}]y_d\right\}_{ii} \,, \tag{2}$$

while, if $(\delta^d_{RR})_{ij} \neq 0$, we generate the invariant

$$J^{(d_i)}_{RR} = \mathrm{Im}\left\{Y_u y_d \delta^d_{RR}\right\}_{ii} \,. \tag{3}$$

Both $J^{(d_i)}_{LL}$ and $J^{(d_i)}_{RR}$ are of the third order in the Yukawa coupling constants. If both $(\delta^d_{RR})_{ij} \neq 0$ and $(\delta^d_{LL})_{ij} \neq 0$, the (C)EDMs emerge at the one-loop level through

$$J^{(d_i)}_{LR} = \mathrm{Im}\left\{\delta^q_{LL} y_d \delta^d_{RR}\right\}_{ii} . \tag{4}$$

The invariant $J^{(d_i)}_{LR}$ is proportional to only one Yukawa coupling constant that is relative to the heaviest quark generation. In the minimal flavor violation hypothesis [6, 7], where the MIs are given by the SM Yukawa couplings y_u and y_d, all the above JIs are suppressed at the same level of $J^{(d_i)}_{\rm SM}$ in the SM. So, large effects to the (C)EDMs can be generated only if new flavor structures in addition to the CKM are present. However, even if these new flavor structures do not introduce any new source of CP violation, $J^{(d_i)}_{LL}$ and $J^{(d_i)}_{RR}$ are generally non-vanishing thanks to their dependence on the CKM phase.

The JI contributing to the up-quark (C)EDMs are simply obtained from the corresponding down-quark JI by exchanging the suffixes u and d. For simplicity, in the following discussion we focus our attention on the down-quark (C)EDMs; the extension to the up-quark case is straightforward.

The effective Lagrangian necessary to evaluate all the relevant BLO effects to the (C)EDMs includes effective couplings of $H^\pm$ with fermions and of $\tilde{\chi}^\pm$ ($\tilde{g}$) with fermion-sfermion.

The determination of the $\tan\beta$-enhanced effects passes through the following steps [7, 8]: *i)* evaluation of the effective dimension-four operators appearing at the one-loop level which modify the Yukawa couplings; *ii)* expansion of the off-diagonal squark mass terms by means of the MI approximation; *iii)* diagonalization of the quark mass terms and derivation of the relevant effective interactions.

Starting from step *i)*, the interaction Lagrangian for the Higgs and fermion fields, in the SU(2)$\times$U(1) symmetric limit, is expressed by

$$\begin{aligned}\mathcal{L} &= \overline{u}_{Ri}\left[\overline{y}_{ui}\overline{V}_{ij}H_2 - (\epsilon^u\overline{V})_{ij}H_1^\dagger\right]q_{Lj}\\ &+\overline{d}_{Ri}\left[\overline{y}_{di}\delta_{ij}H_1 - \epsilon^d_{ij}H_2^\dagger\right]q_{Lj} + \mathrm{h.c.}\,,\end{aligned} \tag{5}$$

where ϵ^q_{ij}s are the non-holomorphic radiative corrections appearing when heavy SUSY particles are integrated out from the effective theory [7, 8, 9], while $\overline{V}$ ($\overline{y}_f$) are the CKM matrix (Yukawa couplings) defined in the "bare" CKM basis, namely the CKM basis as defined before the inclusion of the ϵ^q_{ij} corrections.

Passing to step *ii)* we derive, after the electroweak symmetry breaking, the radiative correction to the down-quark mass matrix $(\delta m_d)_{ij}$ as follows

$$\begin{aligned}(\delta m_d)_{ij} \simeq \Big[&\overline{m}_{d_i}\epsilon\delta_{ij} + \overline{m}_{d_i}\Big(\epsilon_Y(\overline{V}^\dagger\Delta\overline{V})_{ij} - \epsilon_L(\delta^d_{LL})_{ij}\Big)\\ &-\epsilon_R(\delta^d_{RR})_{ij}\overline{m}_{d_j} + \epsilon_{LR}\overline{m}_b(\delta^d_{RR}\Delta\delta^d_{LL})_{ij}\Big]t_\beta\,.\end{aligned} \tag{6}$$

In the $(\delta m_d)_{ij}$ evaluation, we included the effects from flavor-violation sources (MIs) in the squark mass matrices. In Eq. (6) t_β=$\tan\beta$, Δ=diag(0, 0, 1) and, for equal SUSY masses and $\mu > 0$, it turns out that $6\epsilon_{LR} = 3\epsilon_L = 3\epsilon_R = \epsilon = \alpha_s/3\pi$ and $\epsilon_Y = -A_t/|A_t|\times(y_t^2/32\pi^2)$ with A_t defined in the convention where the left-right stop mass term is $-m_t(A_t + \mu/t_\beta)$; moreover, in Eq. (6), as in the rest of this Letter, hat and bar symbols refer to diagonal matrices and bare quantities, respectively.

Passing to step *iii)* we define the "physical" CKM basis through the unitary transformations

$$d'_L = V_{d_L}d_L\,,\quad u'_L = V_{u_L}\overline{V}\,u_L\,,\quad d'_R = e^{-i\hat{\theta}_d}V_{d_R}d_R\,, \tag{7}$$

so that the "physical" CKM matrix is given by $V = V_{u_L}\overline{V}V^\dagger_{d_L}$. Allowing for complex entries in $(\delta m_d)_{ij}$, the

phase rotations $\exp(-i\hat{\theta}_d)$ are introduced to make the quark masses real.

Expanding $V_{d_{R,L}}$ at the first order around the diagonal, *i.e.*, $V_{d_{R,L}} \simeq \mathbf{1} + \delta V_{d_{R,L}}$, we find, by means of Eq. (6), the following expressions,

$$(\delta V_{d_L})_{3i} \simeq -\frac{\epsilon_L t_\beta}{1+\epsilon t_\beta}(\delta^d_{LL})_{3i} + \frac{\epsilon_Y t_\beta}{1+\epsilon t_\beta} V_{3i}\,,$$
$$(\delta V_{d_R})_{i3} \simeq \frac{\epsilon_R t_\beta}{1+\epsilon t_\beta}(\delta^d_{RR})_{i3}\,. \tag{8}$$

The phase parameters $\theta_{d1,2}$ in $\hat{\theta}_d$ are derived from

$$m_{di} e^{i\theta_{di}} \simeq \overline{m}_{di} + (\delta m_d)_{ii} + m_b (\delta V_{d_R})_{i3} (\delta V^\star_{d_L})_{i3}\,, \tag{9}$$

and $\theta_{d3} \simeq 0$. V_{u_L} is obtained by V_{d_L} by exchanging $\overline{V}$ with $\overline{V}^\dagger$ and $\tan\beta$ with t_β^{-1}. Finally, we can derive the effective $H^\pm$ couplings with fermions

$$\bar{t}_L d_{Ri} H^+ \!\rightarrow y_{d_i}\left[\frac{\overline{m}_{di}}{m_{di}} e^{i\theta_{di}} \overline{V}_{3i} + \frac{\overline{m}_b}{m_{di}} e^{i\theta_{di}} V^{*i3}_{d_R}\right], \tag{10}$$
$$\bar{t}_R d_{Li} H^+ \!\rightarrow y_t t_\beta^{-1}\left[(1-\epsilon t_\beta) V_{3i} - t_\beta^2 \sum_{j\neq 3} V^{3j}_{u_L} V_{ji}\right]. \tag{11}$$

The charged Higgsino ($\tilde{H}^\pm$) couplings are also given as

$$\tilde{t}^*_R \overline{\tilde{H}}{}^-_{2R} d_{Li} \;\rightarrow\; -y_t (V^\dagger_{u_L} V)_{3i}\,, \tag{12}$$
$$\tilde{t}^*_L \overline{\tilde{H}}{}^-_{1L} d_{Ri} \;\rightarrow\; (\overline{V}\hat{\overline{y}}_d V^\dagger_{d_R})_{3i}\, e^{-i\theta_{d3}}\,, \tag{13}$$

where $i = 1, 2$. The $\tilde{g}$ interactions are described by

$$\tilde{d}^*_{Li}\, \overline{\tilde{g}}{}^a_R\, d_{Lj} \;\rightarrow\; \sqrt{2} g_s (V^\dagger_{d_L})_{ij}\,,$$
$$\tilde{d}^*_{Ri}\, \overline{\tilde{g}}{}^a_L\, d_{Rj} \;\rightarrow\; -\sqrt{2} g_s (V^\dagger_{d_R})_{ij}\, e^{-i\theta_{di}}\,. \tag{14}$$

The above Feynman rules have been computed performing the rotations for the quark fields (see Eq. (7)) in the "bare" Lagrangian and implementing, at the same time, the vertex corrections to the relevant interactions. Other couplings, such as those for the wino or the bino, are also derived in a similar way.

Let us notice that the $H^\pm$ and $\tilde{H}^\pm$ couplings with the right-handed down quarks can be proportional to the heaviest-quark Yukawa coupling when the right-handed squark mixing is non-vanishing. The last mechanism provides the main enhancement factor for the BLO contributions. In addition, at the BLO, $\tilde{g}$ interactions develop flavor- and/or CP-violating couplings that also lead to sizable effects on the (C)EDMs.

Although our numerical results have been obtained including the full set of contributions, in the following, for simplicity, we report only the dominant contributions to the hadronic EDMs. In particular: *i)* we neglect the effects proportional to $J^{(d_i)}_{LL}$ because suppressed by a factor of m_{d_i}/m_b compared to the dominant contributions; *ii)* we neglect the sub-leading effects provided by the electroweak couplings g_1 and g_2. For later convenience, let us define $\omega_{1,2}$ as

$$\omega_1 \;=\; \mathrm{Im}\left[(\delta^d_{LL})_{i3}(\delta^d_{RR})_{3i}\right]\,, \tag{15}$$
$$\omega_2 \;=\; \mathrm{Im}\left[V^*_{3i}(\delta^d_{RR})_{3i}\right]\,, \tag{16}$$

to which $J^{(d_i)}_{LR}$ and $J^{(d_i)}_{RR}$ are proportional, respectively. The gluino/squarks contribution to the (C)EDMs is

$$\left\{\frac{d_{d_i}}{e},\; d^c_{d_i}\right\}_{\tilde{g}} \simeq \frac{\alpha_s}{4\pi}\frac{m_b}{m^2_{\tilde{q}}}\frac{m_{\tilde{g}}\mu}{m^2_{\tilde{q}}}\frac{t_\beta}{1+\epsilon t_\beta}\Bigg[\omega_1\, f^{(3)}_{\tilde{g}}(x) + f^{(2)}_{\tilde{g}}(x)\left(\frac{(\epsilon_L+\epsilon_R)t_\beta}{1+\epsilon t_\beta}\omega_1 - \frac{\epsilon_Y t_\beta}{1+\epsilon t_\beta}\omega_2\right) + f^{(1)}_{\tilde{g}}(x)\left(\frac{2\epsilon_R(\epsilon_L\omega_1 - \epsilon_Y\omega_2)t^2_\beta}{(1+\epsilon t_\beta)^2} - \frac{\epsilon_{LR} t_\beta}{1+\epsilon t_\beta}\omega_1\right)\Bigg], \tag{17}$$

where $x = m^2_{\tilde{g}}/m^2_{\tilde{q}}$ and $f^{(1,2,3)}_{\tilde{g}}(x)$ are $-2/27(-5/18)$, $2/45(7/60)$, and $-4/135(-11/180)$ for (C)EDM, respectively. The first contribution in Eq. (17) refers to the LO contribution proportional to the JI $J^{(d_i)}_{LR}$. The second and third lines of Eq. (17) contain pure BLO terms. As regards the LO term, we have included a resummation factor, whose impact is very sizable.

The first $H^\pm$ effects to the (C)EDMs appear at the BLO [10]. In the present work, in addition to the contributions discussed in Ref. [10], we have evaluated the entire set of BLO effects that are well approximated by

$$\left\{\frac{d_{d_i}}{e},\; d^c_{d_i}\right\}_{H^\pm} \simeq \frac{\alpha_2}{16\pi}\frac{m_b}{m^2_{H^\pm}}\frac{m^2_t}{m^2_W}\frac{\epsilon_R t_\beta}{(1+\epsilon t_\beta)^2} f_{H^\pm}(z)\times \Big[(1-\epsilon t_\beta)\,\omega_2 + \epsilon_L t_\beta\,\omega_1\Big] \tag{18}$$

where $z = m^2_t/m^2_{H^\pm}$ and $f_{H^\pm}(z)$ is such that $f_{H^\pm}(1) = 7/9(2/3)$. We note that Eq. (18) receives dominant effects both from $J^{(d_i)}_{RR}$ and $J^{(d_i)}_{LR}$.

Charginos contribute to $J^{(d_i)}_{LL}$ already at the LO, so, the corresponding (C)EDMs are suppressed by m_{d_i}. At the BLO, a new effect proportional to $J^{(d_i)}_{RR}$ (and thus proportional to m_b) is generated by the charged-Higgsino/squark diagrams leading to

$$\left\{\frac{d_{d_i}}{e},\; d^c_{d_i}\right\}_{\tilde{\chi}^\pm} \simeq \frac{\alpha_2}{16\pi}\frac{m_b}{m^2_{\tilde{q}}}\frac{m^2_t}{m^2_W}\frac{A_t\mu}{m^2_{\tilde{q}}}\frac{\omega_2\epsilon_R t^2_\beta}{(1+\epsilon t_\beta)^2} f_{\tilde{\chi}}(y)\,, \tag{19}$$

where μ is the $\tilde{H}^\pm$ mass, $y = \mu^2/m^2_{\tilde{q}}$ and $f_{\tilde{\chi}}(1) = -5/18(-1/6)$.

The above expressions for the EDMs, *i.e.*, Eqs. (17)-(19), have been obtained by inserting effective (one-loop induced) vertices into the one-loop expressions for the EDMs. We would like to note that such an approach accounts for all the non-decoupling ($\tan\beta$-enhanced) contributions to the EDMs but it cannot provide the full

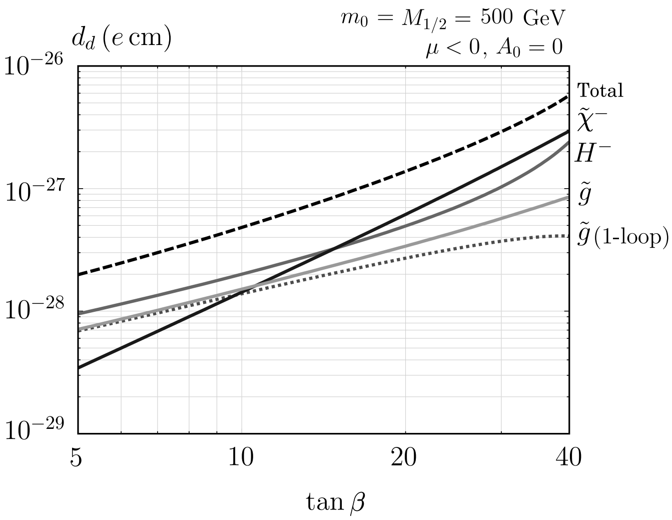

FIG. 1: Contributions to the down-quark EDM assuming a CMSSM spectrum with $m_0 = M_{1/2} = 500$ GeV, $\mu < 0$, $A_0 = 0$, $\delta^d_{RR} = V$ and $\delta^d_{LL} = 0$ at the GUT scale.

set of two-loop effects. The latter requires a full diagrammatic calculation, which is outside the scope of this work.

For instance, the expression of Eq. (18) is valid as long as the typical supersymmetric scale $M_{\rm SUSY}$ is sufficiently larger than the electroweak scale $m_{\rm weak}$ ($\sim m_W,\ m_t$) and the mass of the charged Higgs boson $m_{H^\pm}$. Therefore, our results can be regarded as the zeroth-order expansion in the parameters $(m^2_{\rm weak}, m^2_{H^\pm})/M^2_{\rm SUSY}$ of the full computation. However, it has been shown in Ref. [11] that this zeroth-order approximation works very well, at least in the $b \to s\gamma$ case, even for $m_{H^\pm} \geq M_{\rm SUSY}$, provided $M_{\rm SUSY}$ is sufficiently heavier than $m_{\rm weak}$. This finding should also hold in our case, considering that both $b \to s\gamma$ and the EDMs arise from a similar dipole transition.

Moreover, in the present analysis, we have neglected potentially relevant two-loop effects, proportional to large logarithms of the ratio $M_{\rm SUSY}/m_{\rm weak}$, stemming from: *i)* the different renormalizations of Yukawa couplings in the Higgs/Higgsino vertices, and *ii)* the anomalous dimensions of the magnetic and chromo-magnetic effective operators. These two classes of terms become important when the scale of the supersymmetric colored particles is significantly higher than the W boson and top quark masses.

However, we emphasize that the new two-loop effects we are dealing with in the present work are comparable to and often larger than the leading one-loop effects to the EDMs induced by gluino/squarks loops. Thus, a full inclusion of all the two-loop effects to the EDMs is not compulsory (although desirable) in a first approximation.

In order to appreciate the impact of these new contributions for the EDMs, let us compare the size of BLO and LO effects. In Fig. 1, we assume a CMSSM spectrum with GUT scale conditions $m_0 = M_{1/2} = 500$ GeV, $\mu < 0$, $A_0 = 0$, $\delta^d_{RR} = V$ and $\delta^d_{LL} = 0$; at the low scale, a $\delta^d_{LL} \neq 0$ of order $\delta^d_{LL} = -|c|\,V$ (with $|c| \sim \mathcal{O}(0.1)$) is generated by renormalization-group (RG) effects driven by the CKM. The above scenario finds a natural framework within SUSY GUTs with right-handed neutrinos.

As shown in Fig. 1, the $H^\pm$ and $\tilde{\chi}^\pm$ contributions are typically comparable to the $\tilde{g}$ ones. This is possible because *i)* the $H^\pm$ and $\tilde{\chi}^\pm$ masses (entering in BLO effects) are lighter than the $\tilde{q}$ and $\tilde{g}$ masses (entering in LO effects) in most of the MSSM parameter space; *ii)* $\delta^d_{LL} \lesssim V$ when δ^d_{LL} is radiatively-induced; *iii)* the mass functions for the LO $\tilde{g}$ contributions, $f^{(3)}_{\tilde{g}}(x)$, are more suppressed than those for BLO $H^\pm$ and $\tilde{\chi}^\pm$ contributions.

Moreover, when $\tan\beta$ is large, BLO effects become more significant and they dominate over the LO ones. In the $\tilde{\chi}^\pm$ case, this is explained by the explicit $\tan\beta$-dependence of $(d_d)_{\tilde{\chi}^\pm} \sim \tan^2\beta$ (see Eq. (19)), to be compared with $(d_d)_{\tilde{g}} \sim \tan\beta$ (see Eq. (17)). In the $H^\pm$ case, in spite of the same explicit $\tan\beta$-dependence of $(d_d)_{\tilde{g}}$ and $(d_d)_H$, $(d_d)_H > (d_d)_{\tilde{g}}$ for increasing $\tan\beta$, since m_H is reduced by large RG effects driven by $y_b^2 \sim y_t^2 \sim 1$.

Notice that, the corner of the CMSSM parameter space where the BLO $H^\pm$ effects are particularly enhanced compared to the LO ones, corresponds to the*A-funnel* region (where $m_A \simeq 2\,m_{\rm LSP}$), satisfying the WMAP constraints. If we allow non-universality between the Higgs and the sfermion masses at the GUT scale (the so-called NUHM scenarios), we can typically get a charged Higgs that is lighter than in the CMSSM case and thus the BLO effects become even more important.

The allowed size for hadronic EDMs is obtained by imposing the constraints arising from both flavor-conserving observables as $(g-2)_\mu$, $\Delta\rho$, m_{h^0} and flavor changing processes like $B \to X_s\gamma$, $B \to \tau\nu$, $B_s \to \mu^+\mu^-$, $K_L \to \mu^+\mu^-$, $B - \overline{B}$ and $K - \overline{K}$ mixings [12]. Referring to the example of Fig. 1, all the above constraints are satisfied at the 99% C.L. for the entire range of $\tan\beta$.

The "flavored" (C)EDMs have strong correlations with FCNC observables. As an interesting example, let us mention that, irrespective to the particular choice for the SUSY spectrum, the $\tilde{\chi}^\pm$ and $H^\pm$ contributions to the EDMs are closely related to the NP contributions entering $B \to X_s\gamma$ as

$$(d_d)_{\tilde{\chi}^\pm} + (d_d)_{H^\pm} \simeq -e\frac{\alpha_2}{4\pi}\frac{m_b}{m_W^2}\frac{\epsilon_R t_\beta}{1+\epsilon t_\beta}\,\omega_2\, C_7\,, \qquad (20)$$

where $C_7 = C_7^{\tilde{\chi}^\pm} + C_7^{H^\pm}$ is defined as $\mathcal{B}(B \to X_s\gamma) \simeq 3.15 - 8\,C_7 - 1.9\,C_8$ [13]. A detailed exploration of the intriguing correlation and interplay among FCNC processes and flavored (C)EDMs deserves a dedicated study that goes beyond the scope of this Letter.

In contrast to the hadronic sector, BLO effects to the leptonic EDMs have a rather small impact, thus, they

can be neglected in the first approximation.

In conclusion, our Letter shows that, a correct prediction for the hadronic EDMs within SUSY theories with flavor-changing (but not necessarily CP-violating) soft terms, necessarily requires the inclusion of the BLO contributions presented in this work. In fact, they do not represent just a sub-leading correction to the LO effects, as it typically happens for flavor physics observables, but they provide the dominant effect in large portions of the SUSY parameter space. We also emphasize the importance of further improving the experimental sensitivity on the hadronic EDMs as a particularly interesting and promising probe of New Physics effects.

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